Evaluation of suprascapular nerve neurotization after nerve graft or transfer in the treatment of brachial plexus traction lesions

MARTIN J. A. MALESSY, M.D., PH.D., GODARD C. W. DE RUITER, M.D., KEEF S. DE BOER, M.D., RALPH T. W. M. THOMEER, M.D., Ph.D.

Departments of Neurosurgery and Rehabilitation Medicine, Leiden University Medical Center, Leiden, The Netherlands

Object. The aim of this retrospective study was to evaluate the restoration of shoulder function by means of suprascapular nerve neurotization in adult patients with proximal C-5 and C-6 lesions due to a severe brachial plexus traction injury. The primary goal of brachial plexus reconstructive surgery was to restore biceps muscle function and, secondarily, to reanimate shoulder function.

Methods. Suprascapular nerve neurotization was performed by grafting the C-5 nerve in 24 patients and by accessory or hypoglossal nerve transfer in 29 patients. Additional neurotization involving the axillary nerve was performed in 18 patients. Postoperative needle electromyography studies of the supraspinatus, infraspinatus, and deltoid muscles showed signs of reinnervation in most patients; however, active glenohumeral shoulder function recovery was poor. In nine (17%) of 53 patients supraspinatus muscle strength was Medical Research Council (MRC) Grade 3 or 4 and in four patients (8%) infraspinatus muscle power was MRC Grade 3 or 4. In 18 patients in whom deltoid muscle reinnervation was attempted, MRC Grade 3 or 4 function was demonstrated in two (11%). In the overall group, eight patients (15%) exhibited glenohumeral abduction with a mean of 44 ± 17° (standard deviation [SD]; median 45°) and four patients (8%) exhibited glenohumeral exorotation with a mean of 48 ± 24° (SD; median 53°). In only three patients (6%) were both functions regained.

Conclusions. The reanimation of shoulder function in patients with proximal C-5 and C-6 brachial plexus traction injuries following suprascapular nerve neurotization is disappointingly low.

KEY WORDS • brachial plexus injury • grafting • nerve transfer • neurotization • suprascapular nerve

Adults with severe brachial plexus traction lesions frequently present with rupture or avulsion of spinal C-5 and C-6 nerves, which results in the loss of active glenohumeral abduction, exorotation, and elbow flexion. The C-7, C-8, and T-1 spinal nerves may be involved as well, affecting the function of the lower arm and hand. It is generally agreed that the primary goal of nerve repair in cases involving these lesion types is restoration of biceps muscle function. The reanimation of shoulder function is the second goal.14,23 In adults who have undergone brachial plexus reconstruction, good results of shoulder function recovery have been reported.1,4,7,10,21–23,28,34,35 Interpretation of the data presented, however, is difficult for the following reasons. First, the results pertaining to different types and localizations of lesions have been pooled—for instance, superior trunk lesions have been grouped with axillary nerve lesions and traction lesions with gunshot wounds and sharp wounds. Second, results of multiple nerve repair techniques for shoulder function reanimation have been pooled, such as those of various grafting procedures with transfers and those of neurolysis or end-to-end repair with grafting. Third, the results of nerve repair are sometimes combined with those of secondary surgery without specifying the contribution of the constituting parts. Furthermore, the severity of the lesions found intraoperatively has not been specified in detail: information on histology of nerve stumps is not provided and the length of the grafts is not specified. Last, the analysis and scoring methods applied to assess postoperative shoulder function are generally not clearly outlined. For these reasons, it remains unclear which degree of shoulder function recovery should be attributed to a particular repair technique.

In the present study, we evaluated the restoration of shoulder function in patients who had undergone suprascapular nerve neurotization in a selected group of 53 patients with severe proximal brachial plexus traction injuries in whom a superior trunk repair was not possible. Restoration of shoulder function was the second goal of surgery; priority was given to elbow flexion reanimation. Suprascapular nerve neurotization was performed by C-5 grafting as well as accessory or hypoglossal nerve transfer. Functional outcome was analyzed to determine specific factors affecting functional recovery.

Abbreviations used in this paper: EMG = electromyography; ES = electrical stimulation; MR = magnetic resonance; MRC = Medical Research Council; ROM = range of motion; SD = standard deviation.
TABLE 1

Grafting of the C-5 nerve to the suprascapular nerve in 11 patients*

<table>
<thead>
<tr>
<th>Case No</th>
<th>Diagnosis</th>
<th>Additional Nerve Repair</th>
<th>Age (yrs)</th>
<th>Trauma-Op Interval (days)</th>
<th>Graft Length (cm)</th>
<th>% of Myelin</th>
<th>MRC Grade</th>
<th>Supra</th>
<th>Infra</th>
<th>Biceps</th>
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* ADTS = anterior division of the superior trunk; AV = avulsion; AX = axonotmesis; AXN = axillary nerve; ICN = intercostal nerve; infra = infraspinatus muscle; intrafor = intraforaminal; LC = lateral cord; MC = musculocutaneous nerve; N = neurotmesis; pec = pectoral nerve; rad lat med = lateral root of the median nerve; rad med med = medial root of the median nerve; supra = supraspinatus muscle; TI = inferior trunk; TM = medial trunk; TS = superior trunk; XII = hypoglossal nerve.
† Glenohumeral abduction 20°, total abduction 45°.
‡ Grafting to both suprascapular nerve and musculocutaneous nerve (or lateral cord or anterior division of the superior trunk).

TABLE 2

Grafting of the C-5 nerve to the suprascapular and axillary nerves in 13 patients*

<table>
<thead>
<tr>
<th>Case No</th>
<th>Diagnosis</th>
<th>Additional Nerve Repair</th>
<th>Age (yrs)</th>
<th>Trauma-Op Interval (days)</th>
<th>Graft Length (cm)</th>
<th>% of Myelin</th>
<th>MRC Grade</th>
<th>Supra</th>
<th>Infra</th>
<th>Deltoid</th>
<th>Biceps</th>
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<td>25–50</td>
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<td>C-5 &amp; C-6 N, partial C-7-C8 AV</td>
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<td>C-5 &lt; C-6</td>
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<td>4th-6th ICN–MC, 3rd ICN–pec, C4–rad lat med</td>
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<td>&gt;75</td>
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<td>159</td>
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<td>11 (2)</td>
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<td>77</td>
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<td>11</td>
<td>&lt;25</td>
<td>50–75 C-5 &lt; C-6</td>
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* MCD = medial cord; rad = radial nerve; SN = suprascapular nerve.
† Glenohumeral abduction/exorotation 45° and 15°, respectively.
‡ Glenohumeral abduction 80°.
Suprascapular nerve neurotization in brachial plexus lesions

Clinical Material and Methods

Patient Population

One hundred fifty-five adults with severe BPTI were surgically treated at the Department of Neurosurgery of the Leiden University Medical Center. Intraplexal nerve grafting and/or extra–intraplexal nerve transfer was performed. The primary goal was to restore active elbow flexion and, secondarily, to reanimate active glenohumeral function. In this retrospective study, inclusion criteria consisted of the following. 1) There should be intra- or juxtaforaminal rupture or avulsion from C-5 and C-6. 2) The proximal stump in nerve grafting for shoulder function reanimation was the C-5 spinal nerve. 3) The distal stump of nerve repair was the suprascapular nerve or both the suprascapular nerve and axillary nerve (patients with a neurotmetic lesion limited to the posterior division of the superior trunk or of the axillary nerve and/or suprascapular nerve as part of a more extended brachial plexus lesion were not included). 4) Each distal stump was connected to only one proximal donor stump (a combination of two donors to one distal stump hampers the assessment of the contribution of each individual donor stump to the result). 5) Intraplexal–intraplexal nerve transfers were conducted when the C-5 outlet was not available or suited for grafting to reanimate shoulder muscles. 6) The postoperative follow-up period was at least 2 years.

Also excluded were patients with an apparent axonotmetic lesion of the suprascapular nerve or axillary nerve. The contribution to functional recovery resulting from grafting or from transfer to the suprascapular nerve is difficult to determine when some degree of spontaneous recovery in the axonotmetic axillary nerve has occurred. Fifty-three patients (47 men, six women) met these criteria and constitute the basis of the present study (Tables 1–4). The majority of patients had sustained their injuries in traffic accidents. Clinically, all patients exhibited normal function of anterior serratus, rhomboid, and trapezius muscles. Before surgery, all patients underwent needle EMG examination to confirm the complete absence of activity at maximum voluntary effort. This investigation included the trapezius muscle to exclude an accessory nerve lesion. A computerized tomography myelography study was obtained prior to surgery to detect root avulsions. All patients were shown to have intra- or juxtaforaminal nerve rupture or root avulsion of C-5 and C-6 as well as extensive neuroma formation and scarring of the superior trunk, including the proximal portion of its divisions. In some patients, avulsion of the C7–T1 roots had also occurred. Plain radiography revealed scapular fractures in nine patients (17%) and humeral fractures in nine patients (17%); one of whom had sustained a combination of both fractures. The mean age of the patients at surgery was 24.6 ± 8.4 years (± SD; median 23.3 years). The mean interval between trauma and operation was 128.6 ± 71.4 days, median 117 days). The mean follow-up period was 3.3 ± 1.7 years (median 3 years). At 6-month intervals,

<table>
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<th>Diagnosis</th>
<th>Additional Nerve Repair</th>
<th>Age (yrs)</th>
<th>Trauma–Op Interval (days)</th>
<th>Graft Length (cm)</th>
<th>MRC Grade</th>
<th>Supra</th>
<th>Infra</th>
<th>Biceps</th>
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<td>201</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>C5–C6–AV</td>
<td>3rd–5th ICN–MC</td>
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<td>203</td>
<td>4</td>
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<td>0</td>
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</tr>
<tr>
<td>21</td>
<td>C-5/C-6/C-7 AV, C-8/T1 AX</td>
<td>3rd–5th ICN–MC</td>
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<td>117</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td></td>
</tr>
</tbody>
</table>

* Pec med = medial pectoral nerve.
† Glenohumeral abduction 45˚ (Case 2), 45˚ (Case 5), 30˚ (Case 6), 40˚ (Case 12), and 50˚ (Case 16).
‡ Glenohumeral exorotation 45˚ (Case 11), 60˚ (Case 12), and 70˚ (Case 16).

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TABLE 3
Accessory to suprascapular nerve transfer in 21 patients*
the force exerted by the deltoid, supraspinatus, infraspinatus, and biceps muscles was assessed according to the MRC scale. In evaluating the active elbow flexion, the function of the brachioradial muscle and a possible so-called Steindler effect from lower-arm muscles were considered. Repeated postoperative needle EMG studies of the target muscles were performed in all patients. Reinnervation was considered. None of the patients exhibited joint contractures that affected by the reinnervated infraspinatus or teres minor muscles. The total functional range is defined as the sum of both true glenohumeral exorotation and the glenohumeral excursion. The total functional range is defined as the sum of both true glenohumeral exorotation and the glenohumeral excursion.

**Examination of Shoulder Function**

The shoulder function evaluation was adapted from that reported by Narakas and applied as follows. First, the passive ROM of abduction, exorotation in adduction, and exorotation in maximal abduction was examined, focusing on the presence of contractures. Second, the active range of abduction and exorotation was analyzed and divided in two distinct parts: namely, true glenohumeral motion and the thoracoscapular rotations. True glenohumeral abduction occurs in the frontal plane and was defined as the angle "α" formed by the position of the humerus and the medial scapular margin at maximal abduction. Thoracoscapular rotation was defined as the angle "β" formed by the position of the medial scapular margin at rest and at maximal abduction. This was measured by simultaneous palpation of the upper part of the extended arm with one hand and the inferior angle of the scapula with the other during an attempt of maximal abduction. The total functional abduction range "α+β" is defined as the sum of α and β (Fig. 1). The patient was asked to stand straight—thus, lateroflexion and extension of the spine (Fig. 2) was not appreciated by the examiner, and neither was glenohumeral elevation resulting from pectoralis major activity. To examine whether the force was sufficient to abduct against gravity (MRC Grade 3), the patient was asked to tilt the spine to the contralateral side while keeping the arm maximally abducted. The glenohumeral abduction in the acquired ROM could only be effect- ed by contraction of the supraspinatus and/or deltoid muscle reinnervated as a result of grafting or transfer.

**Surgical Technique**

**Grafting.** The surgical technique was similar to that previously described. The entire trajectory of the brachial plexus was exposed. Root avulsions were confirmed by the emptiness of the intervertebral foramen. In the case of nerve rupture, the neuroma was excised and, depending on the appearance of the nerve stump, additional resection of scarred nervous tissue was performed. In the case of neuroma-in-continuity, ES of spinal nerve muscles was applied. General anesthesia did not include muscle blocking agents. If corresponding muscle contractions were absent, resection was continued until the architecture of the cross-sectional area appeared normal through the operating microscope. Frozen-section examination was used to assess fibrosis/neuroma in the C-5 and/or C-6 proximal stump. In addition, a neuropathologist assessed semiquantitatively the total quantity of myelin, represented by the stained myelin of the fibers, in the entire cross-sectional area of the donor stump. The results were classified as follows: 1) less than 25%; 2) greater

<table>
<thead>
<tr>
<th>Case</th>
<th>Diagnosis</th>
<th>Nerve Repair</th>
<th>Age (yrs)</th>
<th>Trauma-Op Interval (days)</th>
<th>Graft (cm)</th>
<th>MRC Grade</th>
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<td>XI–SN, XII–AXN, 3rd-5th ICN–MC</td>
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<td>2</td>
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<td>C5–T1 AV</td>
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<td>17</td>
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<td>4</td>
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<td>15</td>
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<td>6</td>
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<td>XII–SN, ansa XII–XII dist, 3rd–5th ICN–MC, XI–pec</td>
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<td>7</td>
<td>C5–C6 AV</td>
<td>XII–SN, XI–AXN, ansa XII–XII dist, 3rd–5th ICN–MC, C4–rad lat med</td>
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<td>8</td>
<td>C5–T1 AV, C4 N, XI AX/N</td>
<td>XII–SN, 3rd–5th ICN–MC, C4–rad lat med</td>
<td>28</td>
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* Ansa = cervical ansa hypoglossal nerve; dist = distal branch; supraclav med = medial supraclavicular nerve; XI = accessory nerve.
Suprascapular nerve neurotization in brachial plexus lesions

In all cases, the priority of repair was restoration of biceps function. The decision-making process is schematically depicted in Fig. 4. If only one spinal nerve emerged from the intervertebral foramen (most often C-5), it was used to reinnervate the biceps preferentially if the following criteria were met. 1) Computerized tomography myelography demonstrated intact roots. 2) The fascicular pattern of the nerve cross-section on frozen examination appeared normal. 3) The frozen section showed more than 50% myelin and only slight fibrosis. 4) The size of the cross-sectional area was equal to or larger than the musculocutaneous nerve fascicles in the lateral cord or musculocutaneous nerve stump. If both C-5 and C-6 contained myelinated fibers, C-6 was selected to reinnervate the biceps when the quantity of myelin was equal to or greater than that of C-5 and when the cross-sectional area was equal to or larger than C-5. When only one stump was available, most often C-5, it was exclusively used for biceps muscle reanimation when the C-5 cross-sectional area was equal to that of the musculocutaneous nerve fascicles in the lateral cord or musculocutaneous nerve distal stump.

The proximal C-5 stump was used as a lead-out for a graft to the suprascapular nerve in the following situation. First, C5-suprascapular nerve grafting was undertaken in addition to grafting from C-5 to musculocutaneous nerve.

Fig. 1. The active range of abduction and exorotation was divided in two distinct parts: true glenohumeral motion and the total ROM, which combines the glenohumeral excursion and thoracoscopic rotations. True glenohumeral abduction occurs in the frontal plane and was defined as the angle α formed by the position of the humerus and the medial scapular margin at maximal abduction. Thoracoscopic rotation was defined as the angle β formed by the position of the medial scapular margin at rest and at maximal abduction. This was measured by simultaneous palpation of the upper part of the extended arm with one hand and the inferior angle of the scapula with the other during an attempt of maximal abduction. The total functional abduction range ϑ is defined as the sum of α and β.

Fig. 2. Photograph of a 23-year-old patient with a severe brachial plexus traction lesion with C-5 spinal nerve rupture and C-6 avulsion. Nerve grafting from C-5 to both suprascapular nerve and musculocutaneous nerve was performed. Supraspinatus and infraspinatus muscle strength recovered to MRC Grade 1. Glenohumeral abduction is 0° and thoracoscopic rotation (β) is ± 40°. To compensate for the lack of glenohumeral abduction, some abduction is achieved based on thoracoscopic rotation with intact trapezius, levator scapulae, rhomboid, and serratus anterior muscles in combination with lateroflexion of the spine. We do not consider this type of postoperative function a result of the procedure.
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preferentially used for biceps muscle reinnervation and not for shoulder reanimation when it fit the criteria mentioned above. The accessory nerve distal to the innervating branch of the sternocleidomastoid muscle was followed in its trajectory through the posterior triangle of the neck. The status of the accessory nerve was assessed by using ES. The accessory nerve transfer procedure was abandoned when the preoperative neurological examination showed weakness of the trapezius muscle, which was confirmed by weak trapezius contractions following accessory nerve ES. Our intention was to perform a direct coaptation between the accessory nerve and suprascapular nerve. To achieve this, two steps were taken. First, the retro- or infraclavicularity displaced suprascapular nerve stump was neurolyzed and transposed back to the original suprascapular region as far up as possible. Second, the entire trajectory of the accessory nerve distal from the branch to the upper portion of the trapezius muscle was exposed and transected as distally as possible. The accessory nerve was then transferred to the lateral neck region. Both stumps were coapted by using 10-0 sutures and/or fibrin glue.

In eight patients with at least C-5 and C-6 avulsion we used either the hypoglossal nerve or intercostal nerve transfer for shoulder function reanimation, which was in addition to accessory nerve transfer in five of these patients. The surgical technique that was used to dissect free and transfer the hypoglossal nerve or intercostal nerve has been described previously.17,18

Intraoperative Findings

Of 53 patients, 15 presented with rupture of C-5 and 20 with rupture of both C-5 and C-6.

Thirty-two C-5 and 15 C-6 stumps were used as donor sites for grafts. Advanced resection of the remaining C-5 and C-6 stumps up to the intervertebral foramen continued to reveal fibrosis and no myelin. One patient was shown to have an avulsion of C-5, and 17 had an avulsion of both C-5 and C-6, as confirmed by the emptiness of the intervertebral foramen. The C7–T1 spinal nerves were totally avulsed in 21 patients (Tables 1–4).

Reconstructive Procedures

Overall, 59 grafting procedures and 85 transfers were performed in the group of 53 patients. The specifications of the brachial plexus reconstructions of each individual patient are summarized in Tables 1 to 4. A C-5 proximal stump was available for grafting in 32 patients. Adhering to the decision-making process illustrated in Fig. 4, eight C-5 stumps (25%) were exclusively used for biceps muscle reinnervation.

In 24 patients the C-5 was used as a lead-out for a graft to the suprascapular nerve (Tables 1 and 2). In 11 of these patients, the C5–suprascapular nerve grafting was the only procedure for the reanimation of active glenohumeral shoulder function. These cases are referred to as the C5–suprascapular nerve group (Table 1). In the remaining 13 patients, C5–axillary nerve grafting was performed in addition to the C5–suprascapular nerve grafting. These cases are referred to as the C5–suprascapular nerve and axillary nerve group (Table 2). Nerve transfers to the suprascapular nerve were performed in 26 patients. Additional grafting procedures or transfers such as intercostal to medial pectoral were

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**Fig. 3. True glenohumeral exorotation is defined as the angle between the position of the 90° (actively or passively) flexed elbow resting against the belly and the position of the flexed elbow after exorotation with the upper arm in adduction until the scapula starts rotating.**

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fascicles when the C-5 cross-sectional area was larger than that of the musculocutaneous nerve fascicles in the lateral cord or musculocutaneous nerve distal stump. Second, a single graft was led out from C-5 to the suprascapular nerve when the C-5 cross-sectional area equaled that of the suprascapular nerve and the frozen-section examination showed preferentially more than 50% myelin.20 Grafts were led from C-5 to both the suprascapular nerve and axillary nerve when the C-5 cross-sectional area was large enough for the coaptation of more than two grafts and C-5 did not fit the aforementioned criteria for biceps muscle reinnervation. The donor C-5 stump was not used as a donor site for grafts when frozen-section examination of specimen up to the foramen continued to show predominant neuramotous tissue or revealed ganglion cells.

For distal coaptation, maximal attempts were undertaken to reduce the gap between C-5 and both suprascapular nerve and axillary nerve. Therefore, the retro- or infraclavicularity displaced suprascapular nerve stump was neurolyzed and transposed back to the original suprascapular region as far up as possible. Far-distal dissection to exclude a two-level lesion of the suprascapular nerve, for instance, by rupture out of the supra- and infraspinatus muscles or rupture at the level of the scapular notch, was not systemically performed. The axillary nerve was cut as proximally as possible after freeing it from the posterior cord until fascicular intermingling with thoracodorsal or radial nerve fascicles was encountered. Incidentally, the axillary nerve fascicles could be freed up to the level of the distal portion of the posterior division of the superior trunk, which was then the level of distal coaptation. In the majority of cases cabled sural grafts were used to bridge the gap. The length of the graft was documented in the surgical record. Coaptations were secured by means of 10.0 sutures and/or fibrin glue.

These nerve reconstructive procedures were part of an extended brachial plexus reconstruction, including, for example, intercostal–musculocutaneous nerve transfer (Tables 1 and 2).

**Nerve Transfer.** The accessory–suprascapular nerve transfer was applied when both C-5 and C-6 were avulsed or when one proximal stump was available. This stump was
Suprascapular nerve neurotization in brachial plexus lesions

FIG. 4. Flow diagram depicting the applied surgery-related decision-making process. The C5–suprascapular nerve graft was performed in addition to grafting from C-5 to musculocutaneous fascicles when the C-5 cross-sectional area was larger than that of the musculocutaneous fascicles in the lateral cord or musculocutaneous distal stump. One graft was led out from C-5 to suprascapular nerve when the C-5 cross-sectional area equaled that of the suprascapular nerve and frozen-section analysis showed preferentially more than 50% myelin. Grafts were led from C-5 to both the suprascapular nerve and axillary nerve when the C-5 cross-sectional area was large enough for the coaptation of more than two grafts and C-5 did not fit the criteria for biceps muscle reinnervation. AXN = axillary nerve; BP = brachial plexus; C-5 = C-5 donor stump; C-6 = C-6 donor stump; ICN–MCN = intercostal-musculocutaneous nerve transfer; XIN–SSN = accessory to suprascapular nerve transfer.

performed as well, but their evaluation is beyond the scope of this study.

Grafting of C-5 to Suprascapular Nerve

In five of the 11 patients in this group (Table 1), only one graft fit the cross-sectional area of the C-5 stump. The C5–suprascapular nerve grafting was performed in addition to grafting to the anterior division of the superior trunk, lateral cord, or musculocutaneous nerve in the remaining six patients. (Values are presented as the means ± SD.) The mean C5–suprascapular nerve graft length was 5.1 ± 1.9 cm (median 5). The total quantity of myelin in the entire cross-sectional area of the C-5 donor stump was equal to or greater than 50% in eight of 10 patients and was not available in one. The mean age at surgery was 26.5 ± 12.2 years (median 22 years). The mean interval between trauma and surgery was 125.7 ± 71.7 days (median 131 days). The mean follow-up period was 2.8 ± 0.9 years (median 2.9 years).

Grafting of C-5 to Suprascapular Nerve and Axillary Nerve

In this group of 13 patients (Table 2), the mean graft length from C-5 to the suprascapular nerve was 6.3 ± 1.5 cm (median 6 cm). The mean number of grafts from C-5 to the axillary nerve was 1.8 ± 0.7 cm (median 2 cm), and the mean graft length was 10 ± 2.4 cm (median 10.5 cm). The total quantity of myelin in the entire cross-sectional area of the C-5 donor stump was equal to or greater than 50% in nine (70%) of the patients. The mean age at surgery was 25.5 ± 8.3 years (median 23.5 years). The mean interval between trauma and surgery was 151.7 ± 87.5 days (median 129 days). The mean follow-up period was 2.4 ± 0.9 years (median 2.4 years).

Transfer of Accessory Nerve to Suprascapular Nerve

The accessory nerve-suprascapular nerve transfer was the only procedure for shoulder function reanimation in 21 patients (Table 3). Nine patients were shown to have C5–T1 avulsion, and 12 had rupture, avulsion of C-5, or avulsion of C-6 (C-7).

The mean age at surgery was 24.3 ± 7.3 years (median 23.3 years). The mean interval between trauma and operation was 128.4 ± 63.5 days (median 121 days). The mean follow-up period was 4 ± 2.3 years (median 3.1 years).

Combined Accessory Nerve, Hypoglossal Nerve, or Intercostal Nerve Transfer to Suprascapular Nerve and Axillary Nerve

In this group of eight patients, accessory nerve–supra-
scapular nerve transfer in combination with hypoglossal action potentials and recruitment patterns as befitting re-innervation in the supraspinatus muscle in 43 (84%) of 51 available examinations. In nine (17%) of 53 patients supraspinatus muscle strength of MRC Grade 3 or 4 was demonstrated. Electromyographic studies of the infraspinatus muscle showed reinnervation in 37 (74%) of 50 examinations. In four (8%) of the 53 patients infraspinatus muscle force of MRC Grade 3 or 4 was achieved. Deltoid muscle re-innervation was attempted in 18 patients. In 15 (88%) of 17 available studies EMG showed reinnervation. Two patients (11%) exhibited MRC Grade 3 or 4 function.

In the entire group, eight patients (15%) attained gleno-humeral abduction (α) with a mean of 44 ± 17° (median 45°) and four patients (8%) exhibited glenohumeral exorotation (α) with a mean of 48 ± 24° (median 53°). Only three patients (6%) regained both functions. Thirty-six (68%) of 53 patients exhibited biceps muscle force of MRC Grade 3 or greater.

Grafting of C-5 to Suprascapular Nerve

In this group, postoperative needle EMG of the supraspinatus and infraspinatus muscle demonstrated reinnervation in nine of 10 available studies. Despite this evidence of restored neural continuity to the suprascapular nerve, only one (9%) of 11 patients exhibited supraspinatus muscle strength of MRC Grade 3: glenohumeral abduction (α) was 20° and total abduction (θ) was 45° (Table 1). Glenohumeral abduction did not recover in the remaining 10 patients. Restoration of active exorotation did not occur in any of the 11 patients; however, in seven patients (64%) biceps muscle strength of MRC Grade 3 or greater was shown.

Grafting of C-5 to Suprascapular Nerve and Axillary Nerve

In this group, postoperative needle EMG of the supraspinatus and infraspinatus muscle showed reinnervation in eight (67%) of 12 available studies. Electromyographic examination of the deltoid muscle showed reinnervation in 10 (83%) of 12 examinations. Two (15%) of 13 patients exhibited some supraspinatus muscle strength, one MRC Grade 3 and one MRC Grade 4 (Table 2). Deltoid muscle recovery of MRC Grades 3 and 4, respectively, occurred only in these two patients. The glenohumeral abduction (α) was 45° in one patient and 80° in the other.

One patient (8%) exhibited infraspinatus muscle force of MRC Grade 3. The glenohumeral exorotation (α) was 15°. Seven patients (54%) exhibited biceps muscle force of MRC Grade 3 or greater.

Accessory Nerve–Suprascapular Nerve Transfer

Postoperative needle EMG of the suprascapular muscle showed reinnervation in 18 (85%) of 21 patients; EMG of the infraspinatus muscle showed reinnervation in 14 (70%)
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of 20 available examinations. Only five (24%) of 21 patients, however, exhibited supraspinatus muscle strength of MRC Grades of 3 or 4. Infraspinatus muscle force in three patients (14%) was MRC Grade 3 or 4. Fifteen patients (71%) exhibited biceps muscle force of MRC Grades 3 or 4 (Table 3).

Nerve grafting was necessary to bridge the gap between the accessory nerve and the suprascapular nerve in five (24%) of 21 patients. The mean length of the grafts was 5 ± 1.4 cm (median 6 cm). In these five patients none exhibited supr- or infraspinatus muscle force of MRC Grade 3 or higher.

In 16 (76%) of 21 patients direct coaptation of accessory nerve to suprascapular nerve was achieved. In five (31%) of 16 patients supraspinatus muscle force of MRC Grade 3 or higher was demonstrated. In terms of function, only four patients (25%) exhibited glenohumeral abduction (α) of ± 45˚, which could only be effected by supraspinatus muscle contraction. The total functional abduction range (β) was 60 to 90˚ when thoracoscopic rotation was included. Infraspinatus muscle force in three patients (19%) was MRC Grade 3 or greater. Glenohumeral exorotation in the range from the umbilicus outward was 45˚, 60˚, and 70˚, respectively. Of 16 patients who underwent direct accessory nerve–suprascapular nerve coaptation, both supr- and infraspinatus function of MRC Grade 3 or higher was achieved in only two (13%) (Fig. 5A and B).

Although we did not systematically study the scapular position at rest before and after nerve transfer, we noted a postoperative change in the scapular position in 14 patients. In four patients the scapula had moved upward, and in five patients the inferior angle was laterally rotated. In three patients the scapula had an elevated and laterally rotated position. In the remaining two patients the scapula had moved medially. All of these patients exhibited a normal postoperative function of the serratus anterior and rhomboid muscles. Fifteen (71%) of the overall 21 patients (71%) exhibited biceps muscle force of MRC Grade 3 or greater.

Combined Accessory Nerve, Hypoglossal Nerve, or Intercostal Nerve Transfer to Suprascapular Nerve and Axillary Nerve

In this group, postoperative needle EMG of the supraspinatus muscle showed reinnervation in all eight patients and infraspinatus muscle reinnervation in six (75%) of these patients. Electromyography of the deltoid muscle showed reinnervation in all five patients in whom reinnervation was attempted. Only one of the patients in this group had supraspinatus muscle force MRC Grade 3 after a hypoglossal nerve–suprascapular nerve transfer (Table 4); however, the restored supraspinatus muscle force did not result in functional abduction because volitional control was not restored. The successfully reinnervated muscle could only be contracted by forceful pressure of the tongue against the hard palate or inner wall of the cheek. Infraspinatus muscle recovery greater than MRC Grade 1 did not occur in any patient. Combinations of hypoglossal nerve transfer with transfer of the accessory nerve or intercostal nerve did not lead to glenohumeral abduction or exorotation. Seven patients (88%) exhibited biceps muscle force of MRC Grade 3 or greater.

Elbow Flexion

Nerve grafting was aimed at recovery of biceps muscle function in 28 patients of the total group of 53 patients. Eighteen (64%) attained biceps muscle strength MRC Grades of 3 or greater. The intercostal nerve–musculocutaneous transfer was performed in 21 patients. Fourteen patients (67%) achieved biceps muscle force of MRC Grades of 3 or higher (Tables 1–4).

Discussion

We report the results obtained in 53 patients who harbored intra- or juxtaforaminal neurotmetic lesions or avulsion of C-5 and C-6 in combination with scarring-induced loss of the superior trunk. The primary goal of reconstruction was restoration of elbow flexion. After grafting, 64% of the patients recovered biceps muscle function of MRC Grade 3 or 4, and after intercostal nerve–musculocutaneous transfer 67% of the patients regained this function. This outcome differs slightly from those in two previous studies conducted by our group, which were 74 and 64%, respectively.11,20 Different patient inclusion criteria were used for each study. The aim of the present study, however, was to evaluate the restoration of shoulder function, which was the second goal of nerve repair. Reanimation of shoulder function was primarily pursued by suprascapular nerve neurotization. Repair techniques included grafting from C-5 spinal nerve to the suprascapular nerve, accessory nerve to suprascapular nerve transfer, and hypoglossal nerve to suprascapular nerve transfer. In 18 patients additional neurotization of the axillary nerve was performed as well.

Postoperative needle EMG studies of the suprascapinus, infraspinatus, and deltoid muscles revealed signs of reinnervation in most patients; however, active glenohumeral shoulder function recovery was poor. Comparison of our results with previous reports is difficult because of patient heterogeneity and incomplete specification of lesions and repairs in these studies.

In the present series, several factors independent of the applied repair technique can be identified that may account for the relatively poor shoulder function recovery. First, the apparently poor outcome may be a result of the data analysis. We adapted our evaluation concept from Narakas,24 who emphasized the distinction between true glenohumeral motion and the total ROM, the latter including thoracoscapular movement. Supraspinatus, infraspinatus, and deltoid muscles are involved in glenohumeral motion, whereas trapezius, levator scapulae, rhomboid, and serratus anterior muscles control the scapular thoracic motion.26 If supraspinatus, infraspinatus, and deltoid muscles are paralyzed, functional abduction over a range of ± 45˚ is based on thoracoscapular rotation (Fig. 2). We do not consider this type of postoperative function a result of the surgical procedure.10 Second, we reported on a selected group of upper plexus lesions, in which those cases involving a distally located brachial plexus lesion that affected shoulder function were excluded. Recovery after nerve repair is better in the latter group because of the absence of root avulsion and a shorter distance of the lesion to the target muscle;13 this may explain the superior results in combined series.13 Third, we did not routinely dissect the suprascapular nerve up to the level of the scapular...
notch and therefore may have missed two-level lesions of the suprascapular nerve. In our experience it is technically difficult to assess the status of the suprascapular nerve at the notch level via the anterior approach because the level of the notch is relatively deep. Because the incidence of two-level suprascapular nerve lesions in BPTII has never been systematically analyzed, we do not know to what degree, if any, this factor accounts for our failures. Fourth, plain x-ray films demonstrated scapular fractures or humeral fractures in nine patients (17%). It appears that scapula and/or proximal humerus fractures are frequently associated with soft-tissue lesions at the glenohumeral joint. These lesions may certainly affect outcome after nerve repair. We have not routinely performed MR imaging investigations of the shoulder prior to surgery and we may, therefore, have missed soft-tissue pathological entities. It may be advisable to undertake MR imaging of the shoulder, even arthroscopy, prior to nerve surgery when the scapula or humerus has been fractured to be certain that no soft-tissue pathological entities go undetected. Fifth, there is inherent variability in the normal supraspinatus muscle function. The supraspinatus muscle is known to be primarily active during the initial phase of abduction. Function, therefore, is synergistic with the deltoid muscle. Some of the patients with isolated lesions of the axillary nerve, however, exhibit a normal abduction range, which we have also observed. Others may only be able to abduct the arm over a range of 30°, although the long portion of the biceps is also involved in trick movements to compensate for the loss of deltoid function. Because the range of abduction executed by the supraspinatus muscle alone may vary among individuals, the results of suprascapular nerve neurotization may inherently vary as a consequence.

Nerve Grafting to the Suprascapular Nerve

Different factors may account for the poor functional outcome after the C5-suprascapular nerve grafting that was performed in 24 patients. In grafting for restoration of biceps muscle function, it has been shown that an increase of myelin in the proximal stump is positively correlated to an increase in force. A similar relationship for C5-suprascapular nerve grafting is likely. In the present series, the majority of the C5 stumps contained more than 50% of the normal level of myelin; however, five C5 stumps could serve as a donor site for only one graft. In general, the cross-sectional area of C5 is three- to fivefold greater than that of the suprascapular nerve. The cross-sectional area of the C-5 stumps in these five patients may have been reduced. Only one of five patients regained some abduction. A reduction of the cross-sectional area may certainly affect outcome after nerve repair. We have not systematically analyzed whether the C-5 cross-sectional area is large enough to coapt several nerve grafts, there should be an optimal position to attach the graft to the C-5 stump to reduce misrouting of the original suprascapular nerve axons. The position is the fascicular C-5 area where these axons are already (partially) grouped to form the suprascapular nerve branch. It may be that the amount of fascicular orientation of the original suprascapular nerve axons at the transection level of the C-5 stump affects the results of C5-suprascapular nerve grafting. Moreover, the determination of the position of the graft to the suprascapular nerve on the C-5 stump is arbitrary. The graft to the suprascapular nerve may unintentionally be coapted to a fascicular C-5 area without original suprascapular nerve axons. To the best of our knowledge, the fascicular orientation of suprascapular nerve axons over the length of the C-5 spinal nerve has not been systematically examined. Should an optimal fascicular suprascapular nerve area at the juxtaforaminal level indeed exist, it has not been determined whether, for instance, it is located in the cranial or caudal aspect of the C-5 stump.

Grafting to both suprascapular nerve and axillary nerve from C-5 was performed in another group of 13 patients in whom, in the majority, C-6 was available for grafting to restore biceps function. In this group the results of shoulder functional recovery were not much better than after single suprascapular nerve neurotization—that is, there was no effect of the additional deltoid reinnervation. This might be explained by the length of the grafts (mean 10 ± 2.4 cm, median 10.5 cm), which we had to use to bridge the C5-axillary nerve gap. It appears that the potential for deltoid muscle recovery is limited when long grafts have to be used to bridge a gap between C-5 at the juxtaforaminal level and the axillary nerve.

We found only one study in which C5-suprascapular nerve grafting was reported. Those patients in whom very good functional recovery occurred exhibited an external rotation of 30°. In addition, return of shoulder stability was claimed to be the result of the reconstruction. In our opinion, it is difficult to attribute the transformation of a subluxed glenohumeral joint into a stable joint to successful suprascapular nerve neurotization, when multiple nerve repairs have been performed. Simultaneous reinnervation of the long head of the biceps muscle also contributes to shoulder stability. We do not believe, therefore, that shoulder stability should be the goal for suprascapular nerve neurotization, either by grafting or transfer.

We conclude that grafting from C-5 to the suprascapular nerve with, if the occasion arises, grafting to the axillary nerve is of limited value.

TABLE 5

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>No. of Cases</th>
<th>MRC Grade ≥ 3 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allieu &amp; Cenac, 1988</td>
<td>2</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Oberlin, et al., 1994</td>
<td>1</td>
<td>1 (100)</td>
</tr>
<tr>
<td>Bonnard &amp; Narakas, 1995</td>
<td>32</td>
<td>22 (69)</td>
</tr>
<tr>
<td>Chuang, et al., 1995</td>
<td>25</td>
<td>†</td>
</tr>
<tr>
<td>Merrell, et al., 2001</td>
<td>6</td>
<td>3 (50)</td>
</tr>
<tr>
<td>Dubuisson &amp; Klime, 2002</td>
<td>5</td>
<td>2 (40)</td>
</tr>
<tr>
<td>El-Gamal &amp; Fathi, 2002</td>
<td>4</td>
<td>‡</td>
</tr>
</tbody>
</table>

* Nerve repairs involving neurotization of the trajectory to the axillary nerve were excluded.
† A 20 to 80° abduction with a mean of 45°.
‡ A mean of 30° abduction.
Suprascapular nerve neurotization in brachial plexus lesions

Nerve Transfer

At present, the accessory nerve–suprascapular nerve transfer is widely regarded as a potential nerve reconstructive technique to restore active shoulder function in cases of severe BPIs with upper nerve root avulsion. In 1993 we reported our initial results on the accessory nerve–suprascapular nerve transfer in a small group of patients.16 Probably all centers with extensive experience in surgical nerve treatment of brachial plexus lesions use this transfer method.13 To date, there have been seven studies, comprised of only 75 patients in all,1,5,7,9,10,21,25 pertaining to the recovery of shoulder function in which positive outcome was attributed to the accessory nerve–suprascapular nerve transfer. The differing results of these studies are shown in Table 5. Findings of a meta-analysis23 indicated that the accessory nerve–suprascapular nerve transfer is an effective repair technique; however, the indications for surgery in the various studies differed, and the results were not analyzed or presented uniformly. Birch, et al.,4 reported on 156 accessory nerve–suprascapular nerve transfers, the largest series published to date. Supraspinatus and infraspinatus muscle force of MRC Grade 4 or higher was achieved in approximately two thirds of the patients.8 It is difficult to compare their series with ours because the extent of the lesions was not specified in detail and reconstructive procedures also included superior or trunk grafting. The short interval between trauma and surgery may have favored the outcome13 because some patients underwent surgery within 14 days after trauma. The mean interval between injury and surgery in our series was 128.4 ± 63.5 days (median 121 days).

In the present series the accessory nerve–suprascapular nerve transfer was performed in 21 patients. Additional reanimation of the deltoid muscle was not undertaken in this group. Although EMG signs of reinnervation were present in most patients, restoration of useful shoulder function was limited. Our intention was to perform a direct accessory nerve–suprascapular nerve coaptation. To achieve this goal, we always attempted to mobilize the retro- or infraclavicularly retracted suprascapular nerve to a supraclavicular level, to reduce the gap between the accessory nerve and suprascapular nerve. In addition, the accessory nerve was transected as far distally as was required for direct coaptation, or as was technically possible. Without exception, accessory nerve transection was performed distal to the site of nerve branching to the upper portion of the trapezius muscle. This branching site thus formed the proximal rotation point of the accessory nerve in the transfer.

Despite these efforts, a graft to connect the accessory nerve to the suprascapular nerve was required in approximately 25% of the patients (mean 5 ± 1.4 cm, median 6 cm). In this graft group none of the patients exhibited MRC Grade 4 or higher, whereas in the direct group 18 of 19 (95%) patients achieved MRC Grade 4 or better function (Table 4). Unfortunately, this did not result in improvement in the supraspinatus muscle force of one patient only during an attempt at exorotation. To improve results of shoulder function recovery, we used the hypoglossal nerve as an additional extraplexal source of axons for transfer in combination with the accessory nerve transfer or intercostal nerves (Table 4). Unfortunately, this did not result in shoulder-related functional improvement. In a recent anatomical study it was suggested that the hypoglossal transection site might be a factor in the disappointing results of the hypoglossal transfer because the site affects the number of axons that be-
come available for transfer. The major drawback in the use of the hypoglossal nerve, however, is that the changes in cerebroplasticity required for the restoration of central control do not occur. After hypoglossal nerve transfer, a successfully reinnervated target muscle can only be contracted by forceful pressure of the tongue against the hard palate or inner wall of the cheek. Thus, the functional gain of hypoglossal nerve transfer was virtually nonexistent, despite target muscle recovery to MRC Grade 3 or higher.

Elbow Flexion

Priority in grafting was given to elbow flexion reanimation. Therefore, it is not surprising that flexion recovery was superior to shoulder function recovery. Indeed, when proximal stumps were available for grafting, the stump with the largest quantity of myelin and a greater cross-sectional area was used for neurotization of the musculocutaneous nerve or lateral cord. It is more difficult to understand the discrepancy in results following nerve transfer for elbow flexion or for shoulder function. We used intercostal nerves as proximal outlet in the transfer for the biceps and the accessory nerve as proximal outlet for the shoulder. We have not systematically used intercostal nerves as a donor for shoulder function, nor have we used the accessory nerve for elbow flexion reanimation. These differences make it difficult to compare the results of the applied transfers; however, accessory nerve–musculocutaneous nerve transfer can result in MRC Grade 3 or higher in between 50 and 75% of the patients. This finding indicates that the accessory nerve is a useful donor for nerve transfer, at least for elbow flexion. Intrinsic qualities related to the intercostal nerve and accessory nerve donor nerves play a role in restoring functional outcome for the return of elbow flexion and shoulder function. It seems likely, however, that intrinsic physiological aspects of movement may account for the remarkable difference in levels of recovery between elbow flexion and shoulder function, not in the least because elbow flexion is a relatively simple movement compared with active shoulder function, which requires the coordinated contraction of various shoulder muscles to realize the diversity of movement directions.

Strategy for Nerve Repair

The question arises whether the outcome after shoulder function reanimation in patients with proximal C-5 or C-6 lesions and extensive loss of nerve tissue can be improved by changing the basic surgical strategy without jeopardizing biceps muscle recovery. A possible strategy, when more than one graft can be coapted to the C-5 proximal stump and C-6 is available for the biceps, is to graft C-5 exclusively to the axillary nerve and combine it with accessory nerve–suprascapular nerve transfer. Although we have not yet performed such a procedure, in view of the findings of the present study it is questionable whether this type of change would improve outcome. Whether grafting from the best available proximal stump to axillary nerve and/or suprascapular nerve (instead of using this nerve for the biceps) results in better shoulder function remains to be established.

Good shoulder function outcome is especially important for positioning a functionally intact hand. Recently, two types of intraplexal nerve transfers for patients with C-5 or C-6 lesions have been reported to be successful in combination with accessory nerve–suprascapular nerve transfer—namely, that of the nerve to the long head of the triceps to the axillary nerve; and the medial pectoral nerve to the axillary nerve. The results of extraplexal–intraplexal transfers, such as phrenic nerve to suprascapular nerve, phrenic nerve to axillary nerve; and intercostal nerves to axillary nerve, have been claimed to be rather good; however, the use of the phrenic nerve as a donor has not been widely implemented until now.

Conclusions

Active glenohumeral shoulder function recovery after nerve repair of the suprascapular nerve in patients with proximal C-5 and C-6 lesions and extensive nerve tissue loss is poor. Grafting from C-5 to the suprascapular nerve with, if the occasion arises, grafting to the axillary nerve is of limited value in these patients. At present we recommend only the accessory nerve–suprascapular nerve transfer in patients with good hand function, when direct coaptation is possible and only when grafting to the posterior division of the superior trunk can be realized. The profession and hobbies of the patient, however, should also be considered.

References

Suprascapular nerve neurotization in brachial plexus lesions


Manuscript received February 19, 2004.